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TABLE OF CONTENTS

ABSTRACT

Several new processes have been developed to reduce the mixing and compaction temperatures of hot mix asphalt without sacrificing the quality of the resulting pavement. One of these processes utilizes the Aspha-min® zeolite, a crystalline hydrated aluminum silicate. A laboratory study was conducted to determine the applicability of Aspha-min® to typical paving operations and environmental conditions commonly found in the United States, including the performance of the mixes in quick traffic turn-over situations and high temperature conditions. Aspha-min® was shown to improve the compactability of mixtures in both the SGC and vibratory compactor. Statistics indicated an average reduction in air voids of 0.65 percent. Improved compaction was noted at temperatures as low as 190°F. he addition of zeolite does not affect the resilient modulus of an asphalt mix. The addition of zeolite does not increase the rutting potential of an asphalt mix as measured by the Asphalt Pavement Analyzer. The rutting potential did increase with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder. There was no evidence of differing strength gain with time for the mixes containing zeolite as compared to the control mixes. There is no indication that HMA containing Aspha-min® requires a cure period prior to opening to traffic. The lower compaction temperature used when producing warm asphalt with Aspha-min® may increase the potential for moisture damage as indicated by tensile strength ratio (TSR) and Hamburg tests. However, the addition of hydrated lime mitigated this effect.

A demonstration project was constructed using Aspha-min® zeolite in Orlando, Florida. The warm mix production and compaction temperatures were 35°F less than those used for the control (approximately 300 °F compaction temperature). The laboratory test results on the field mix coincide with the laboratory study. Cores taken one year after placement indicated no increased evidence of moisture damage as compared to the control mix. Overall, Aspha-min® zeolite appears to be a viable tool for reducing mixing and compaction temperatures that can be readily added to hot mix asphalt. Reductions in mixing and compaction temperatures are expected to reduce fuel costs and emissions.

EVALUATION OF ASPHA-MIN® ZEOLITE FOR USE IN WARM MIX ASPHALT

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INTRODUCTION

A number of new processes and products have become available that have the capability of reducing the temperature at which hot mix asphalt (HMA) is mixed and compacted without compromising the performance of the mixture. These new products can reduce production temperatures by as much as 20 percent. North American asphalt mixes are generally heated to 300°F or greater, depending mainly on the type of binder used; mixes are being produced with these new products at temperatures of about 250°F or lower. Lower plant temperatures mean fuel cost savings to the contractor. Findings have shown that lower plant temperatures can lead to a 30 percent reduction in energy consumption (*1*). Lower temperatures also mean that any emissions, either visible or non-visible, that may contribute to health, odor problems, or greenhouse gas emissions, will also be reduced (*2*). The decrease in emissions represents a significant cost savings, considering that 30-50 percent of overhead costs at an asphalt plant can be attributed to emission control (*1*). Lower emissions may allow asphalt plants to be sited in non-attainment areas, where there are strict air pollution regulations. Having an asphalt plant located in a non-attainment area and producing hot mix with a product that allows for a lower operating temperature will allow shorter haul distances which will improve production and shorten the construction period, thus reducing the possible headache of traffic congestion. Warm asphalt mixes will also allow longer haul distances and a longer construction season if the mixes were to be produced at more normal operating temperatures. There is another potential advantage in that oxidative hardening of the asphalt will be minimized with the lower operating temperatures. This may result in changes in pavement performance such as reduced thermal cracking, block cracking, or may cause the mix to be tender when placed.

A number of warm asphalt processes have been identified. This report presents an evaluation of Aspha-min® zeolite. Aspha-min® is a product of Eurovia Services GmbH, based in Bottrop, Germany. Aspha-min® is a manufactured synthetic sodium aluminum silicate, or better known as zeolite. This zeolite has been hydro-thermally crystallized. Zeolites are framework silicates with large empty spaces in their structures that allow the presence of large cations, such as sodium and calcium. They also allow the presence of large cation groups, such as water molecules. Most zeolites are characterized by their ability to lose and absorb water without damaging their crystal structure. Heat can drive off the water contained in the zeolite, which can then act as a delivery system for the new fluid (*3*).

Eurovia's Aspha-min® contains approximately 21 percent water by mass and is released in the temperature range of 185-360°F. When Aspha-min® is added to the mix at the same time as the binder, water is released. This water release creates a volume expansion of the binder that results in asphalt foam and allows increased workability and aggregate coating at lower temperatures.

During the production of HMA, Eurovia recommends that Aspha-min® be added at a rate of 0.3 percent by mass of the mix, which in previous research has shown a potential 54°F reduction in typical HMA production temperatures (*3*). Eurovia also states that all commonly known asphalt and polymer-modified binders can be used, as well as recycled asphalt (RAP). All types of aggregates used in the hot mix industry can also be used, so no changes to a normal mix design process are needed when using zeolite. Aspha-min® zeolite is approximately a 50 mesh material which may be added directly to the pugmill of a batch plant, through the RAP collar, or pneumatically fed into a drum plant using a specially built feeder.

OBJECTIVE

The objective of this study was to perform a laboratory study to determine the applicability of Aspha-min® to typical paving operations and environmental conditions commonly found in the United States, including the performance of the mixes in quick traffic turn-over situations and high temperature conditions.

RESEARCH APPROACH

Table 1 shows the experimental design for the laboratory evaluation of the Aspha-min®. The following sections describe the individual tests that are included in the experimental design.

TABLE 1 Experimental Design for Evaluating the Influence of the Zeolite on Mixture Volumetrics and Performance

Number of samples or replicates to be tested								
	Granite				Limestone			
	PG 58-28		PG 64-22		PG 58-28		PG 64-22	
	No Additive	Zeolite	No Additive	Zeolite	No Additive	Zeolite	No Additive	Zeolite
Mix Designs	9	9	9	9	9	9	9	9
Densification	8	8	8	8	8	8	8	8
Resilient Modulus	24	24	24	24	24	24	24	24
APA Rutting	24	24	24	24	24	24	24	24
Moisture Sensitivity	6	6	6	6	6	6	6	6
Strength Change with Time			10	10			10	10

Mix Design

Two aggregate types (granite and limestone) and two asphalt binder grades (PG 64-22 and PG 58-28) were used to evaluate the Aspha-min®. The mix design replicates a 12.5 mm coarse-graded crushed granite mix produced by Hubbard Construction, Orlando, Florida. The mix design gradation and optimum asphalt contents are shown in Table 2. The same target gradation was used for the limestone aggregate.

TABLE 2 Target Gradations and Asphalt Contents

Sieve Size	% Passing		
	JMF[1]	Granite	LMS[2]
19.0	100.0	99.0	100.0
12.5	90.0	87.9	90.9
9.5	83.0	79.9	83.6
4.75	52.0	49.6	52.7
2.36	34.0	32.2	32.6
1.18	25.0	23.6	23.7
0.600	19.0	18.6	17.5
0.300	13.0	14.7	12.3
0.150	5.0	5.3	6.0
0.075	2.9	2.9	3.1
AC, %	5.3	5.1	4.8

1: Job Mix Formula; 2: Limestone

The job mix formula asphalt content was verified for the granite aggregate using N_{design} = 125 gyrations. For the limestone aggregate, the mix design was re-verified to determine a new optimum asphalt content. Once the mix designs were verified at 300°F (149°C), each combination was then re-evaluated at three lower temperatures (265, 230, and 190°F (129, 110, 88°C)). Volumetric properties for each of the 16 mix design combinations (two binder grades, control and zeolite each at four temperatures) are presented in Tables 3 and 4. Each result represents the average of two samples. From the results of the mix design verifications, asphalt contents of 5.1 and 4.8 percent were determined for the granite and limestone aggregate, respectively. These asphalt contents were used throughout the remainder of the study, whenever test specimens were made.

TABLE 3 Volumetric Mix Design Data for Granite Aggregate

Asphalt	Control or Warm	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
PG 64-22	Control	300	5.1	2.467	88.0	2.365	4.1	13.6	69.6
PG 64-22	Control	265	5.1	2.467	88.2	2.371	3.9	13.3	71.0
PG 64-22	Control	230	5.1	2.467	87.7	2.360	4.4	13.8	68.4
PG 64-22	Control	190	5.1	2.467	87.5	2.356	4.5	13.9	67.6
PG 64-22	Warm	300	5.1	2.457	88.8	2.376	3.3	13.9	76.4
PG 64-22	Warm	265	5.1	2.457	88.9	2.382	3.0	13.6	77.7
PG 64-22	Warm	230	5.1	2.457	88.7	2.378	3.2	13.1	75.5
PG 64-22	Warm	190	5.1	2.457	88.3	2.368	3.6	13.5	73.2
PG 58-28	Control	300	5.1	2.460	88.6	2.372	3.6	13.3	73.2
PG 58-28	Control	265	5.1	2.460	88.3	2.369	3.7	13.4	72.5
PG 58-28	Control	230	5.1	2.460	87.8	2.365	3.9	13.6	71.5
PG 58-28	Control	190	5.1	2.460	87.8	2.359	4.1	13.8	70.2
PG 58-28	Warm	300	5.1	2.458	88.4	2.370	3.6	13.4	73.3
PG 58-28	Warm	265	5.1	2.458	88.2	2.371	3.5	13.4	73.5
PG 58-28	Warm	230	5.1	2.458	88.2	2.369	3.6	13.4	73.1
PG 58-28	Warm	190	5.1	2.458	87.8	2.360	4.0	13.7	71.1

TABLE 4 Volumetric Mix Design Data for Limestone Aggregate

Asphalt	Control or Warm	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
PG 64-22	Control	300	4.8	2.544	85.4	2.433	4.4	15.0	70.8
PG 64-22	Control	265	4.8	2.544	85.1	2.430	4.5	15.1	70.3
PG 64-22	Control	230	4.8	2.544	85.3	2.435	4.3	14.9	71.3
PG 64-22	Control	190	4.8	2.544	85.5	2.439	4.1	14.8	72.1
PG 64-22	Warm	300	4.8	2.544	85.8	2.442	4.0	14.7	72.8
PG 64-22	Warm	265	4.8	2.544	85.8	2.449	3.7	14.4	74.3
PG 64-22	Warm	230	4.8	2.544	85.7	2.444	3.9	14.6	73.2
PG 64-22	Warm	190	4.8	2.544	84.8	2.418	4.9	15.5	68.2
PG 58-28	Control	300	4.8	2.551	85.4	2.445	4.2	14.6	71.5
PG 58-28	Control	265	4.8	2.551	85.7	2.447	4.1	14.5	71.8
PG 58-28	Control	230	4.8	2.551	85.6	2.439	4.4	14.8	70.4
PG 58-28	Control	190	4.8	2.551	85.5	2.439	4.4	14.8	70.3
PG 58-28	Warm	300	4.8	2.545	86.1	2.455	3.5	14.2	75.2
PG 58-28	Warm	265	4.8	2.545	86.2	2.457	3.4	14.1	75.7
PG 58-28	Warm	230	4.8	2.545	85.9	2.444	4.0	14.6	72.9
PG 58-28	Warm	190	4.8	2.545	85.9	2.446	3.9	14.5	73.4

Observations from Tables 3 and 4 indicate that the addition of the Aspha-min® zeolite had little effect on the maximum specific gravity (G_{mm}) of the mixture. Thus, beyond the effect of improved compaction, the addition of 0.3 percent Aspha-min® zeolite is not expected to impact the calculation of volumetric properties. Previous research has indicated that the Superpave gyratory compactor (SGC) was insensitive to compaction temperature (*4*, *5*). In Tables 3 and 4 there are very slight trends of increasing air voids with decreasing temperature for some of the combinations. The addition of the Aspha-min® zeolite resulted in lower air voids than the corresponding control mixture in 14 of the 16 aggregate, binder and temperature combinations. One of the exceptions had the same level of air voids and the other exception, limestone PG 64-22 mixture at 190 °F (88 °C), had 0.8 percent higher air voids than the control. Consequently, the addition of the Aspha-min® zeolite appears to have the potential to reduce the design asphalt content. However, as stated previously, the asphalt contents presented in Table 2 were used for the production of the remaining test samples to reduce the number of variables.

Densification

Once the optimum asphalt contents and volumetric properties for each aggregate/binder combination were determined, test samples were then produced to evaluate the mixes' ability to be compacted over a range of temperatures. These test samples were prepared using oven dried aggregate. Before test samples were made, the anticipated number of test specimens were batched and then randomized for each of the different sets to reduce the variability. This was achieved by compacting a set of six samples per mix at the three lower temperatures mentioned previously (265, 230, and 190°F (129, 110, 88°C)), as well as a set compacted at 300°F (149°C). The mixing temperature was approximately 35°F (19°C) above the compaction temperature. Test samples were compacted using a vibratory compactor, as seen in Figure 1. The vibratory compactor was selected for several reasons. One was that literature suggested that the Superpave gyratory compactor was insensitive to temperature changes. A second reason was that it was found to be easier to produce samples for the Asphalt Pavement Analyzer (APA) with the vibratory compactor than with a Marshall hammer.

Test samples, 6 inches in diameter and 3.75 inches tall, were compacted in the vibratory compactor for a time period of 30 seconds. This was the length of time that produced an air void level of 7 percent in preliminary testing using the PG 64-22 control mixture with the granite aggregate. Each sample was aged for two hours at its corresponding compaction temperature. Once the air void level was determined, these same samples were then used to determine the resilient modulus and APA rut resistance of each mix at the various compaction temperatures.

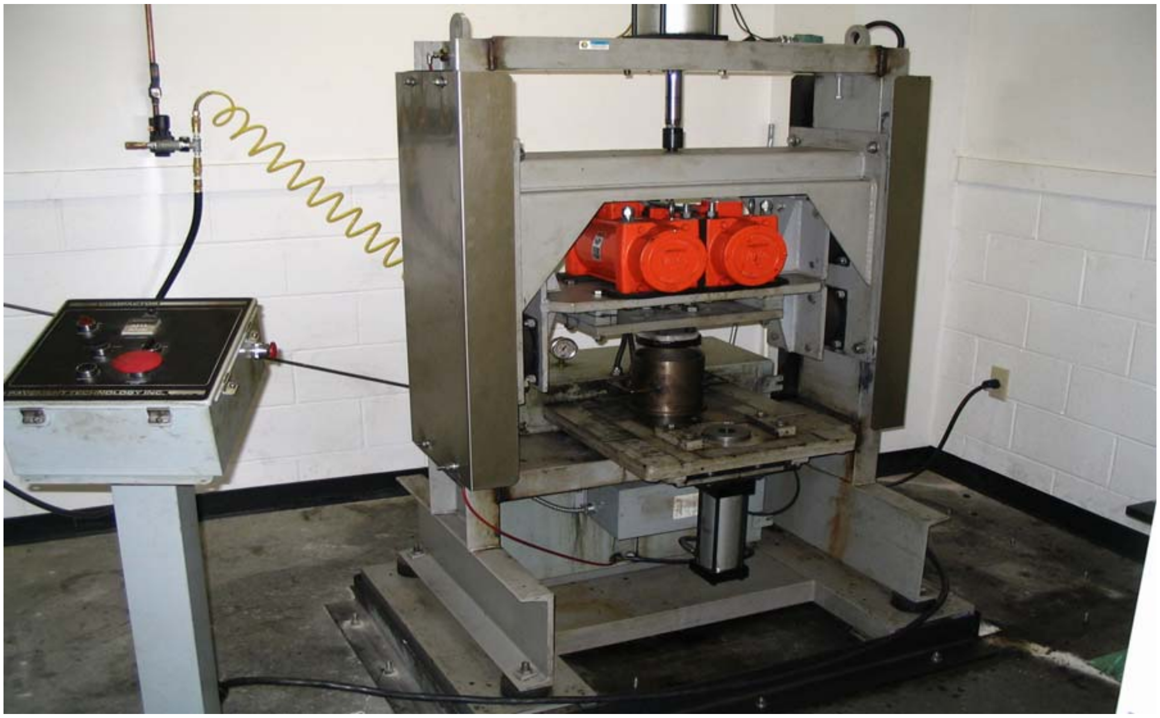

FIGURE 1 Vibratory Compactor used for Compaction of Test Samples

Resilient Modulus

Resilient modulus is a measure of the stiffness of the hot mix asphalt. The indirect resilient modulus was determined according to ASTM D 4123, *Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*. The testing was conducted at 73°F (23°C) as recommended by Lottman (*6*). Since resilient modulus is a non-destructive test, additional testing was conducted on the same set of test samples for each mix combination.

APA Rutting

Once the resilient modulus testing was completed, each mixture set was placed in the APA to determine the rut resistance of each aggregate/binder combination for the different compaction temperatures. All testing was conducted at 64°C to minimize variables in the data. Testing was also conducted using a hose pressure of 120 psi and a vertical load of 120 pounds.

Strength Gain

An evaluation of strength change with time was also conducted because of the possible changes in the stiffness of the asphalt as the water used to microscopically foam the asphalt evaporates with time. It is possible that the mixture strength will change if the evaporation of the water used to foam the asphalt is delayed. If the zeolite improves the workability of a mixture, there may be concern that the workability would not dissipate prior to being opened to traffic, thus creating the potential for rutting.Ten samples of each mix were prepared for short-term and long-term mix aging per AASHTO 312, using the PG 64-22 binder and the granite and limestone aggregates. Mixture strength was evaluated based on indirect tensile strength at 25°C. The indirect tensile strength of the mixture is sensitive to binder (or mastic) stiffness. Indirect tensile strength testing was performed on samples after the aging periods shown in Table 5.

TABLE 5 Strength Gain Experiment Aging Periods

Set	Short Term Aging (hours) at 110 °C (prior to compaction)	Long Term Aging (days) of Compacted Samples at 85 °C
1	2	0
2	4	0
3	2	1
4	2	3
5	2	5

Moisture Sensitivity

If the moisture contained in the zeolite does not completely evaporate during mixing due to the low mix temperatures, water may be left in close contact with the aggregate surface which could in turn lead to increased susceptibility to moisture damage. Therefore, additional test samples were produced and tested according to ASTM D 4867, *Effect of Moisture on Asphalt Concrete Paving Mixtures*, to assess the potential for moisture susceptibility of each mixture combination. The ASTM procedure is similar to the AASHTO T 283 procedure except for the aging times. Several agencies have already eliminated the 72-96 hour cure period found in the AASHTO procedure.

To simulate the actual mixing process of a typical drum plant, a bucket mixer was used to produce the majority of the Tensile Strength Ratio (TSR) test samples. This was selected based on a methodology developed to study the effects of residual moisture on compaction (tender mixes) (*7*). The bucket mixer used can be seen in Figure 2. Before the aggregate was combined with the binder, 3 percent water in addition to the absorption value of each aggregate was added to the mix before it was heated. For example, the granite aggregate had an absorption value of 1.1 percent, so a total of 4.1 percent water by aggregate weight was added to the dry material before the binder was added.

The addition of the aggregate to the bucket mixer took place in two steps because it was found that when the entire batch was added at once, by the time the aggregate was heated to the intended mixing temperature, which was 250°F (121°C), all of the fine material had moved to the bottom of the bucket. So when the binder was added to the aggregate, the fine material was not fully coated. This was alleviated by adding the coarse and fine aggregate separately. The appropriate percentage of moisture was added to the fine aggregate portion and set aside. The coarse aggregate was then added to the bucket, and the appropriate percentage of moisture was introduced to the coarse aggregate (Figure 2) and then it was heated to 250°F (121°C) (Figure 3). Then the fine aggregate portion was added to the bucket and the aggregate was heated back to the intended mixing temperature. When reached, the dust proportion of the blend and binder was added to the bucket and the binder was allowed to thoroughly coat the aggregate. Each bucket mix produced three test samples. During the mixing process, the mix temperature decreased, so each test sample was placed in an oven until the compaction temperature was reached, usually about 10-15 minutes. This process is shown in Figures 2-4.

FIGURE 2 Introduction of Moisture to Aggregate for TSR Samples

FIGURE 3 Heating of Wet Aggregate to Mixing Temperature

FIGURE 4 Hot Mix Asphalt in Bucket Mixer

TEST RESULTS AND DISCUSSION

Densification

As mentioned earlier, samples were compacted in the vibratory compactor over a range of temperatures. The densification results for both the granite and limestone mixes are shown in Figures 5 and 6. From observation of the results in Figures 5 and 6, the addition of zeolite improves compaction over the control mixture for all binder, aggregate, and temperature combinations. This is more pronounced with the PG 64-22, possibly because it is a stiffer binder and has a higher recommended compaction temperature. Observation of Figure 5 also shows that the air void content increased from 300°F to 265°F, but did not increase at the lower compaction temperatures. This is probably due to less aging of the binder or possibly from the coarse nature of the mix. To verify if the coarse nature of the mix had an influence on the densification of the mixtures, a fine gradation was evaluated in the vibratory compactor at the different compaction temperatures, and their bulk specific gravities was determined. The results indicated a gradual increase in the air void content with the decrease in compaction temperature, so the coarse nature of the mix is believed to have some influence in the fluctuation of the densification at the lower compaction temperatures. Also observed was that for three of the four compaction temperatures, the warm mix using PG 64-22 binder had nearly the same air void level as the control mix using the PG 58-28 binder. This suggests that the zeolite additive lowered the mixing and compaction temperature by one asphalt grade. This result was also seen for the limestone aggregate.
Analysis of Variance (ANOVA) was used to analyze the densification data with air voids as the response variable and aggregate type, binder grade, the presence of zeolite, and compaction temperature as factors. Of the main factors, the effect of aggregate type, presence of zeolite and compaction temperature were all significant as well as all of the two-way interactions containing compaction temperature, three of the four three-way interactions were significant (the interaction between compaction temperature, binder grade, and aggregate type was not significant) and the four-way interaction was significant. Aggregate type was the most significant factor followed by whether or not the zeolite was included. Tukey's post ANOVA test showed that the zeolite reduced the air void content by an average of 0.65 percent with a 95 percent confidence interval of 0.49 to 0.81 percent. However, based on the Superpave gyratory compactor results, it seems that the addition of the Aspha-min® zeolite could possibly lower the optimum asphalt content. Lower optimum asphalt contents could affect the compactability of the mixture.

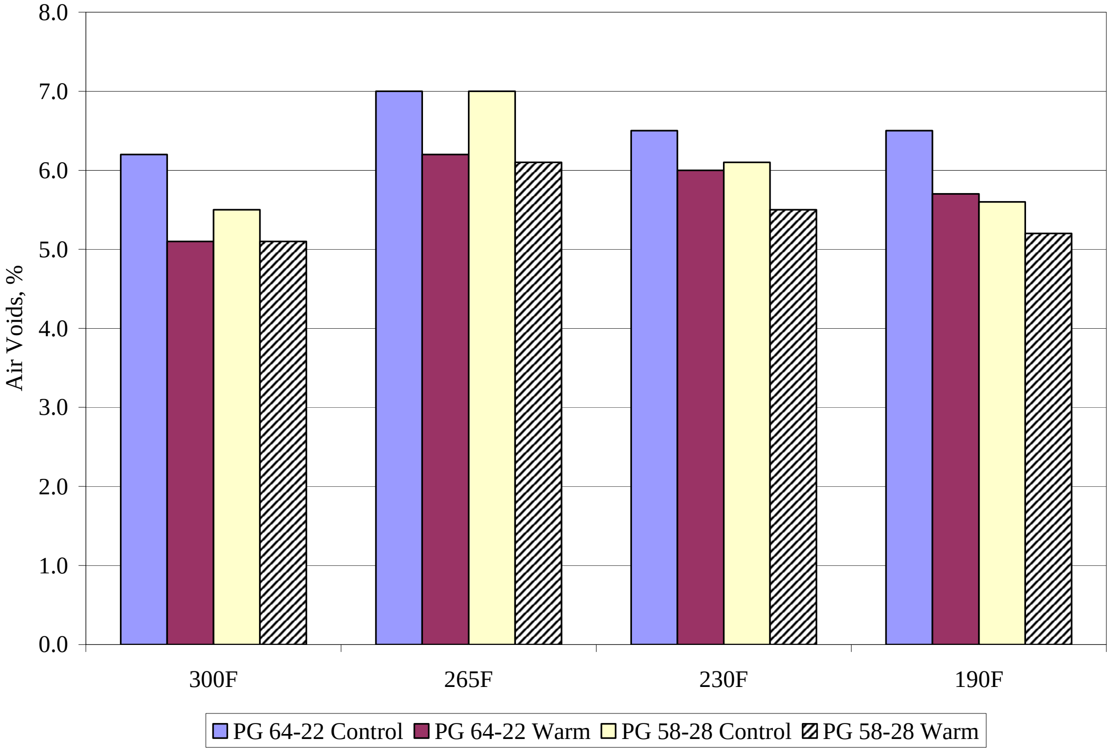

FIGURE 5 Densification Results over Range of Temperatures – Granite Mix

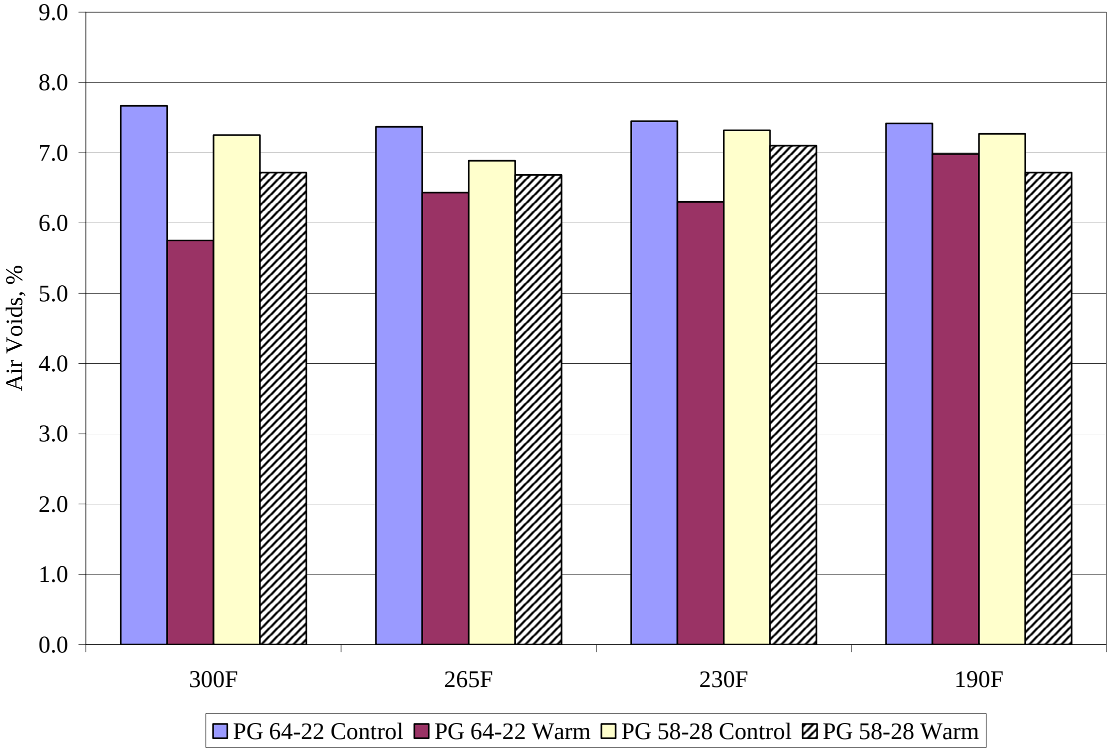

FIGURE 6 Densification Results over Range of Temperatures – Limestone Mix

Resilient Modulus

The results from the resilient modulus tests are shown in Figure 7. The data was separated into four different sets – by both aggregate type and binder grade. Observation of Figure 7 concluded that the resilient modulus decreased as the air void level increased. This was seen for three of the four data sets. The fourth data set showed the opposite or no trend. This may be due to the small range in air void content. Coefficient of determination (R^2) for the data indicated that there is little correlation between air void level and resilient modulus, but this may also be due to the small air void range of the data set.

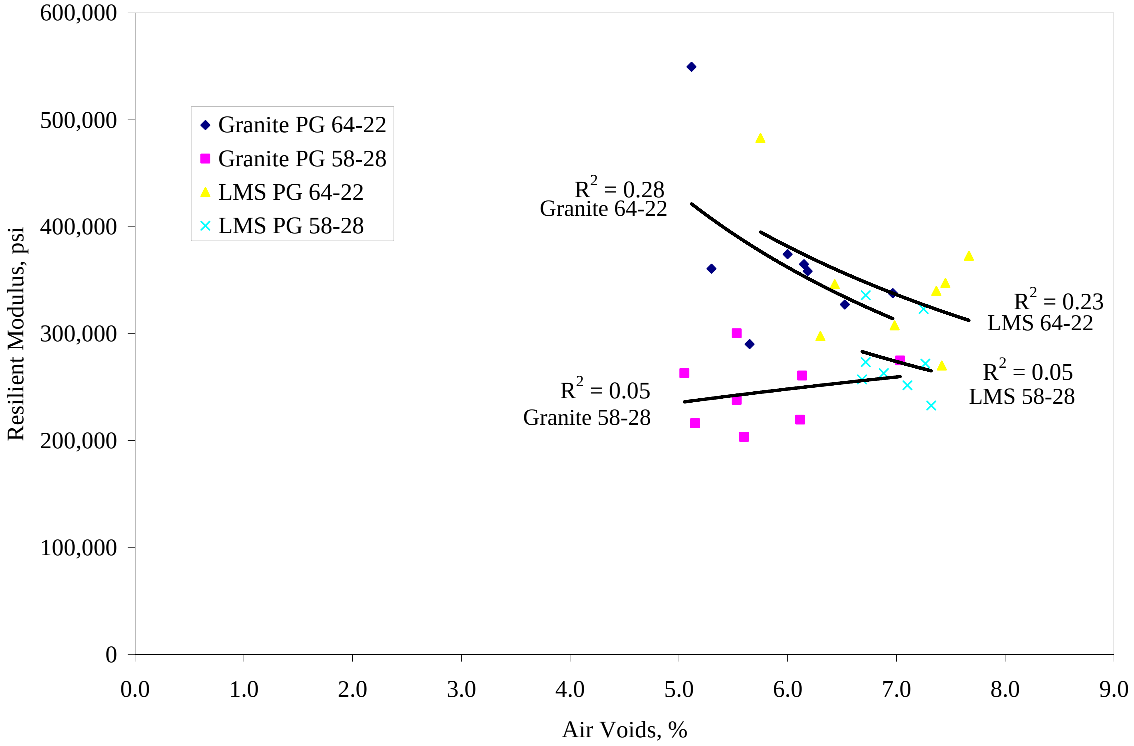

FIGURE 7 Resilient Modulus vs. Air Void Content

An Analysis of Variance (ANOVA) was performed to determine which factors (aggregate type, binder grade, Aspha-min®, and compaction temperature) significantly affect the measured resilient modulus. These results are presented in Table 6. Based on the results, only two factors and two interactions had a significant effect on the resilient modulus. Observation of the F-statistic suggests that the binder grade had the most significant impact on resilient modulus. It can also be noted that the addition of zeolite to the asphalt did not significantly affect the resilient modulus. So the addition of zeolite does not significantly increase or decrease the strength of hot mix asphalt for any compaction temperature.

TABLE 6 ANOVA Results for Resilient Modulus

Source	Degrees of Freedom	Mean Square	F-Statistic	p-value	Significant
Temperature (Temp)	3	9.7846107374	15.27	0.000	Yes
Control or Warm (C or W)	1	1.6103903434	2.51	0.115	No
Binder Grade (Binder)	1	447000000000	69.7	0.000	Yes
Aggregate (Agg)	1	230112071	0.04	0.850	No
Temp*C or W	3	12996556869	2.03	0.112	No
Temp*Binder	3	14195664617	2.22	0.088	No
Temp*Agg	3	3299276396	0.51	0.673	No
C or W*Binder	1	14626382401	2.28	0.133	No
C or W*Agg	1	168169251	0.03	0.872	No
Binder*Agg	1	34937805000	5.45	0.021	Yes
Temp*C or W*Binder	3	22565018975	3.52	0.016	Yes
Temp*C or W*Agg	3	2089469536	0.33	0.806	No
Temp*Binder*Agg	3	4584768602	0.72	0.544	No
C or W*Binder*Agg	1	2954615301	0.46	0.498	No
Temp*C or W*Binder*Agg	3	5902351307	0.92	0.432	No
Error	160	6407073866			
Total	191				

Interaction plots for resilient modulus are shown in Figure 8. From these plots, several conclusions can be made. First, the granite aggregate and the PG 64-22 binder consistently produced the highest resilient modulus values. A greater difference in resilient modulus values was also observed between the PG 64-22 and the PG 58-28 when zeolite was present. Second, the addition of zeolite did not decrease the resilient modulus for either aggregate or for the PG 58-28 binder. As for the PG 64-22, the zeolite actually increased the resilient modulus. Thirdly, the resilient modulus decreased as the compaction temperature decreased. This tends to correspond to the decrease in resilient modulus with increasing air void content. It is also believed that this is related to the decreased aging of the binder (lower asphalt stiffness) with decreasing compaction temperatures.

Further analysis was conducted to determine if there was a statistical difference in the resilient modulus values at the different compaction temperatures. This was accomplished by use of Tukey’s Method. From the results, the resilient modulus values at 300°F (149°C) are statistically different (higher) from those at the other three compaction temperatures. The other compaction temperatures were found to not be statistically different.

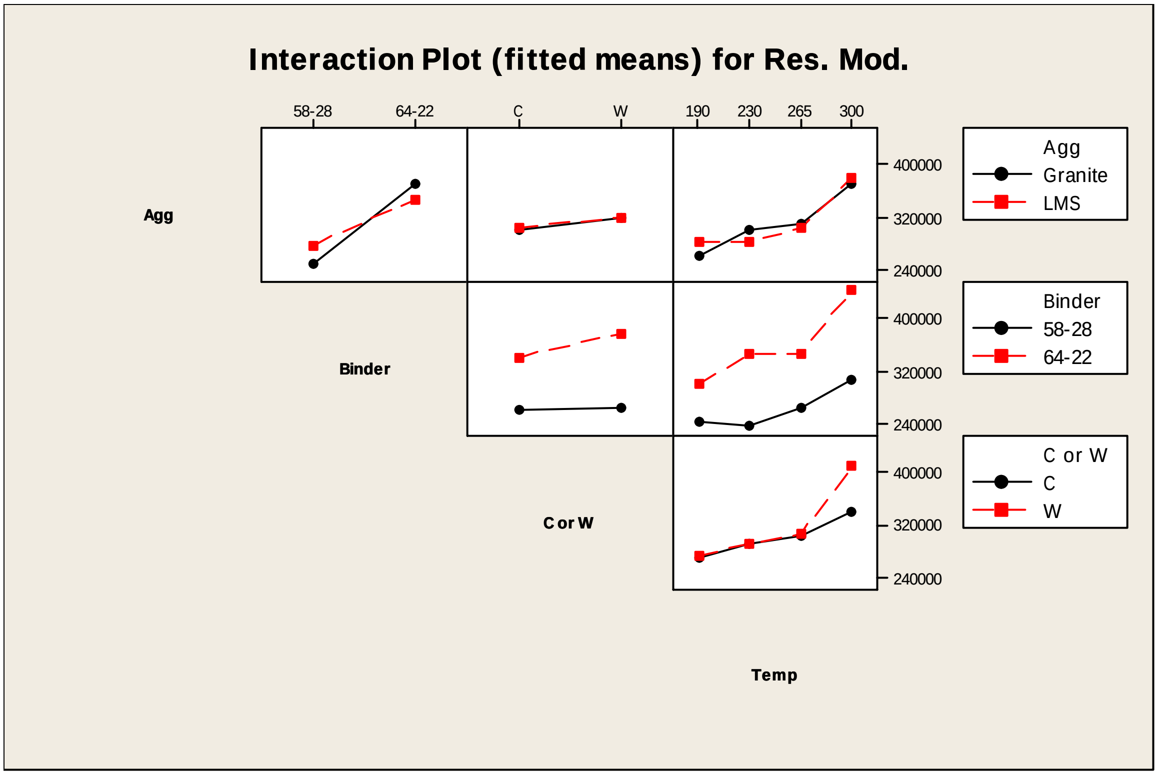

FIGURE 8 Interaction Plots for Resilient Modulus

APA Rutting

Once each set of test samples were tested to determine their resilient modulus value, they were placed in an oven at 64°C (147°F) for a minimum of six hours to ensure that they were equilibrated to the APA test temperature. They were then placed in the Asphalt Pavement Analyzer to determine their rutting potential at a temperature of 64°C (147°F). All rutting results were determined at a temperature of 64°C (147°F) to reduce variability. The rutting results for the granite and limestone aggregates are shown in Figures 9 and 10. The whisker marks in both figures indicate the standard deviation for each set of rut samples.

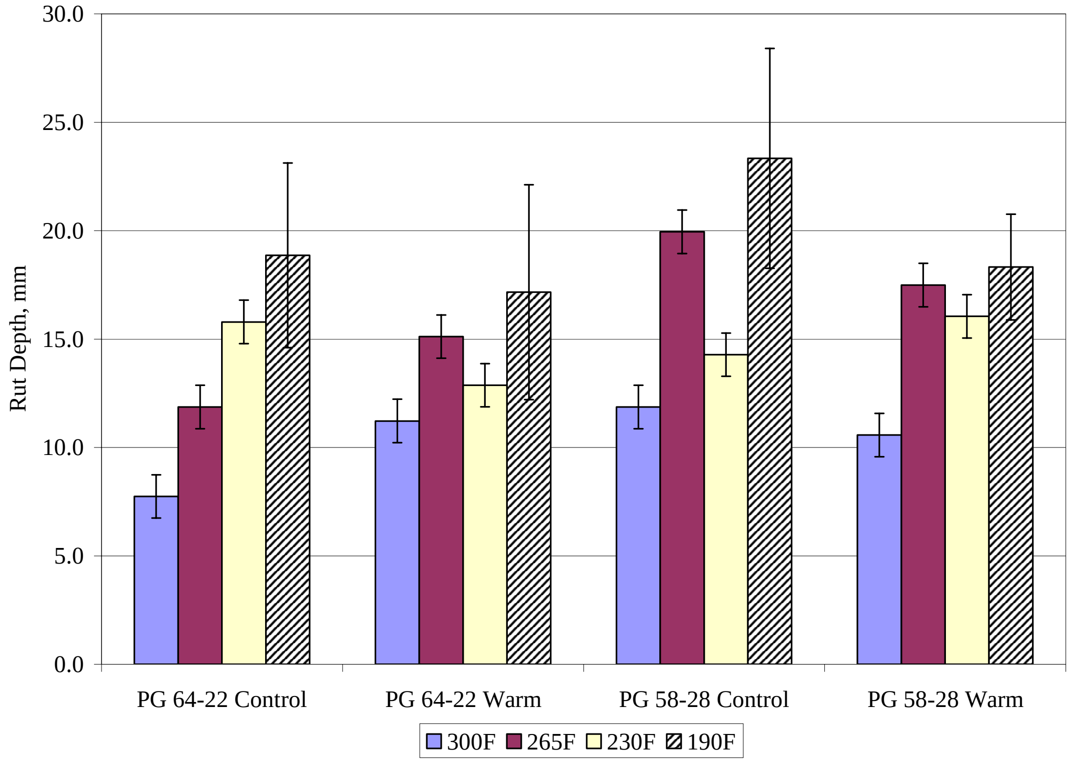

FIGURE 9 APA Rut Depths for the Granite Aggregate

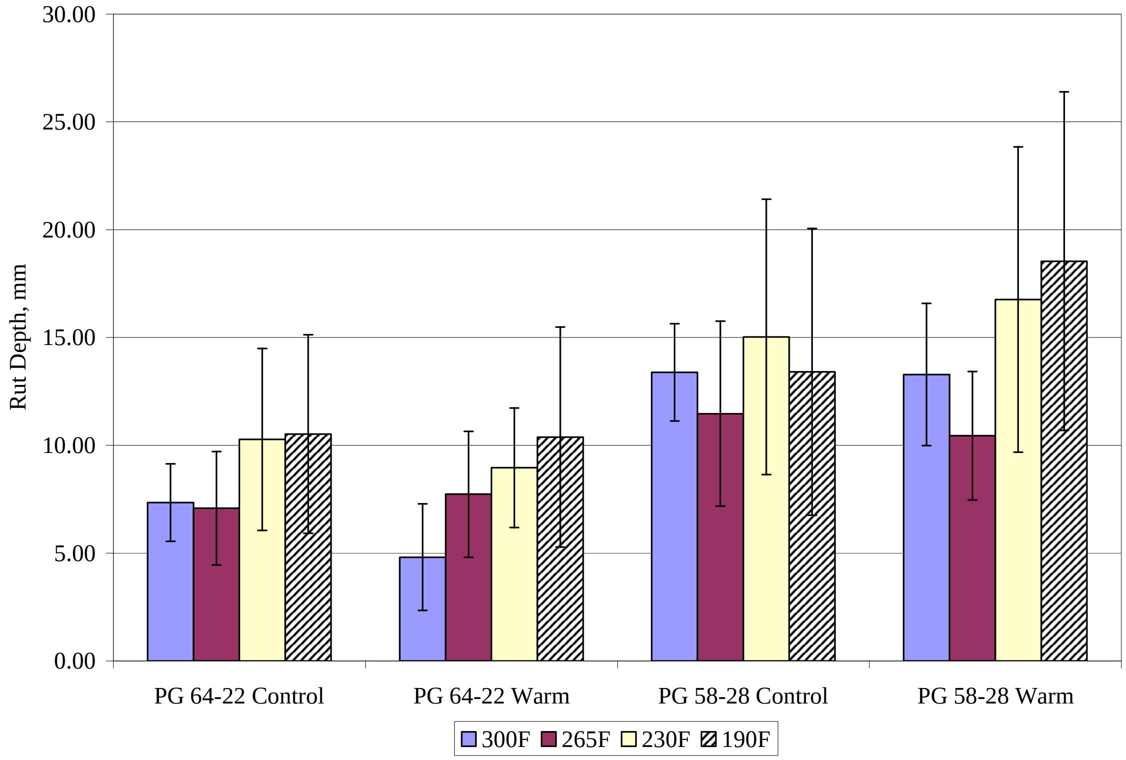

FIGURE 10 APA Rut Depths for the Limestone Aggregate

An ANOVA was performed to determine which factors (aggregate type, binder grade, zeolite, and temperature) significantly affect the measured rut depth. Each of the six samples tested in the APA were treated as a replicate. Results from the ANOVA are presented in Table 7. The results show that three of the four factors and two interactions have a significant effect on rutting. Binder grade has the most impact followed by aggregate type and compaction temperature, based on the F-statistic. The addition of Aspha-min® did not have a significant effect on the measured rut depth. This means that the use of Aspha-min® would not be expected to increase or decrease the rutting potential of an asphalt mixture.

TABLE 7 ANOVA Results for Rut Depth

Source	Degrees of Freedom	Mean Square	F-Statistic	p-value	Significant
Temperature (Temp)	3	325.89	17.61	0.000	Yes
Control or Warm (C or W)	1	1.15	0.06	0.803	No
Binder Grade (Binder)	1	827.63	44.72	0.000	Yes
Aggregate (Agg)	1	745.96	40.31	0.000	Yes
Temp*C or W	3	0.58	0.03	0.993	No
Temp*Binder	3	2.12	0.11	0.951	No
Temp*Agg	3	114.79	6.2	0.001	Yes
C or W*Binder	1	0.00	0.00	0.997	No
C or W*Agg	1	9.97	0.54	0.464	No
Binder*Agg	1	107.9	5.83	0.017	Yes
Temp*C or W*Binder	3	30.91	1.67	0.176	No
Temp*C or W*Agg	3	37.68	2.04	0.111	No
Temp*Binder*Agg	3	34.33	1.86	0.139	No
C or W*Binder*Agg	1	62.12	3.36	0.069	No
Temp*C or W*Binder*Agg	3	15.51	0.84	0.475	No
Error	160	18.51			
Total	191				

Interaction plots for rut depth are illustrated in Figure 11. The interaction plots graphically show how the factors affect the rutting potential. From observation of the interaction plots, several conclusions can be made. One, the limestone rutted less than the granite. Two, the addition of Aspha-min® did not increase or decrease the rutting potential for any factor level combination (aggregate, binder, or compaction temperature). And three, the rut depths increased as the compaction temperature decreased for all factor level combinations.

Further data analysis was performed to determine if there is a significant difference in the rut depths at the four compaction temperatures. This was accomplished by using Tukey’s Method. From the results, it was determined that samples at 300°F (149°C) had the least rutting. Rut depths at 265°F (129°C) and 230°F (110 °C) were not statistically different from one another, but were greater than the rut depths at 300°F (149°C). The samples compacted at 190°F (88°C) had the highest rut depths. This difference in rut depths is not believed to be due to air voids. Instead it is believed to be related to the decreased aging of the binder at the lower compaction temperatures.

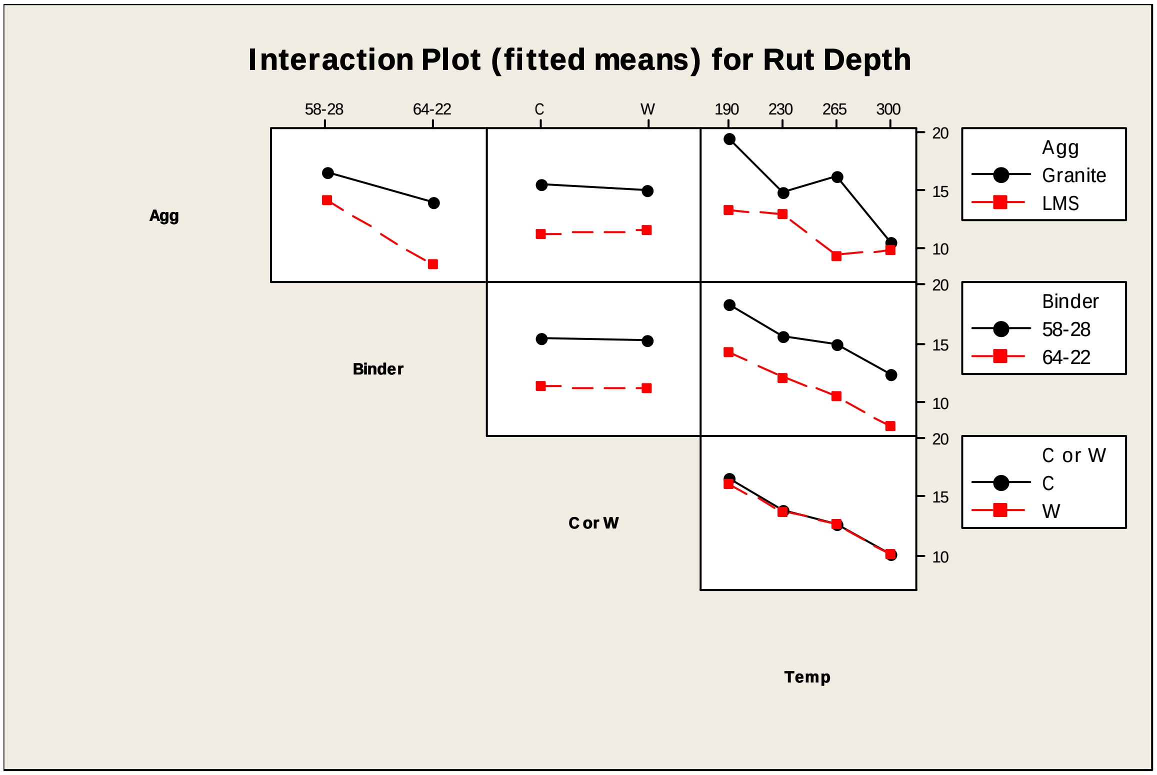

FIGURE 11 Interaction Plots for Rut Depth

Strength Gain

The results from the strength gain experiment for both aggregates are presented in Figures 12 and 13. The results indicated that although the strength varied over the different aging times, there was no change in strength for either the control mix or for the warm mix at a particular age time. This means that there is no evidence to support the need for a cure time before traffic can be allowed on the asphalt mixture containing Aspha-min®.

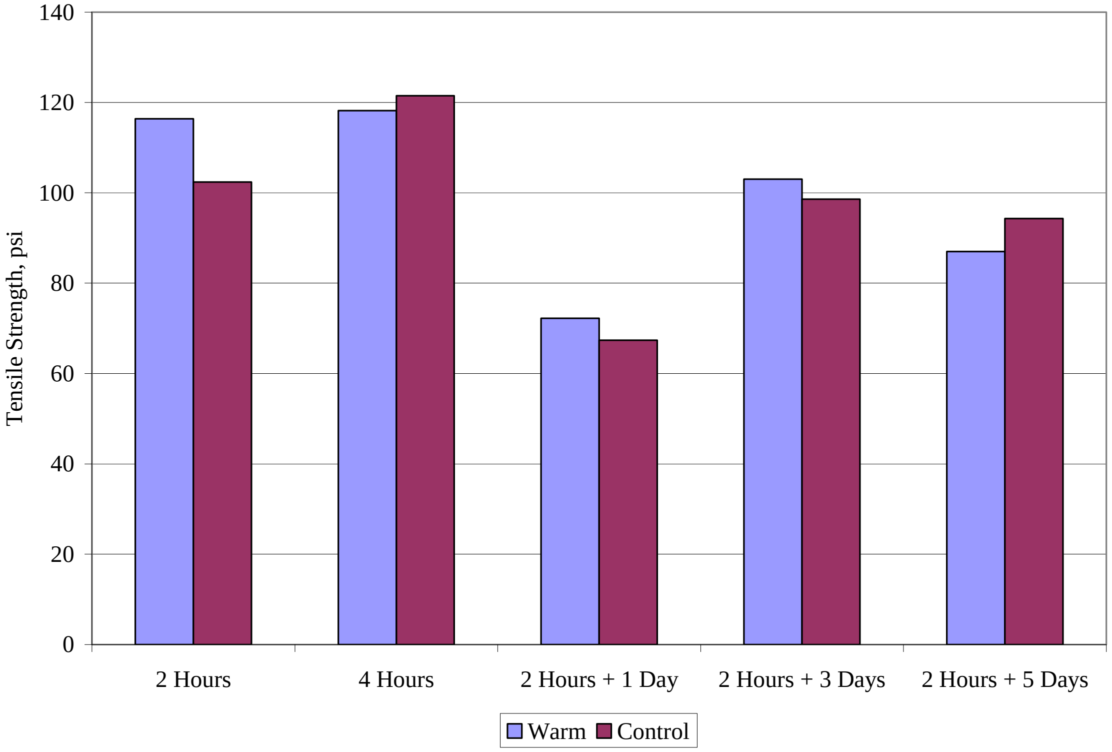

FIGURE 12 Strength Gain Results – Granite Aggregate

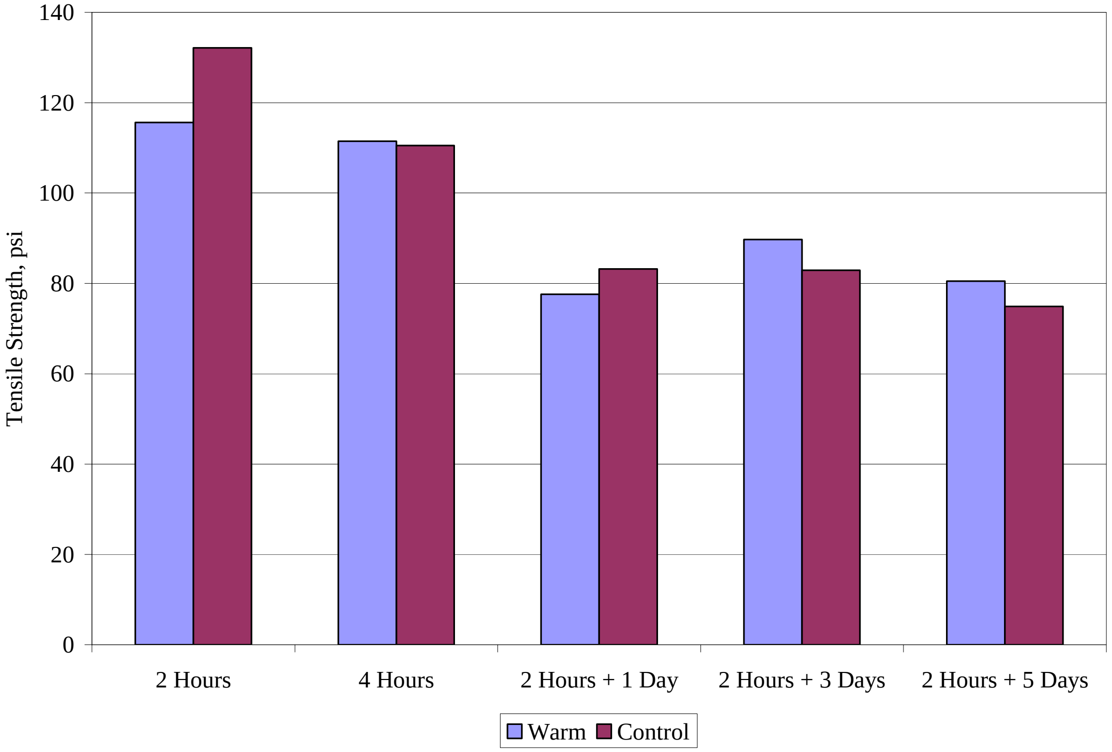

FIGURE 13 Strength Gain Results – Limestone Aggregate

Moisture Sensitivity

As was mentioned before, ASTM D 4867 was used to determine the moisture sensitivity of the mixes. TSR test results for both aggregates are shown in Tables 8. Also included in Table 8 are test results from TSR samples that were prepared from oven dry aggregate in the gyratory compactor after being aged at 300°F (149°C) for two hours, as stated in ASTM D 4867. This testing was conducted to see what kind of behavior the zeolite exhibited in the mixture. From the test results, the presence of zeolite decreased the TSR value, but still resulted in an acceptable value.

Once this testing was concluded, TSR samples were then produced at a lower compaction temperature (250°F (121°C)) using the bucket mixer, as previously discussed in this report. Initially, testing was performed without the presence of any type of anti-stripping agent. Results from this testing showed that the zeolite lowered the TSR value as compared to the control mixture (Table 8); the resulting TSR value does not satisfy the recommended minimum value for Superpave mixes (minimum of 0.80).

TABLE 8 Tensile Strength Results for Granite and Limestone Aggregates

Aggregate	Mix Type	Unsaturated, psi	Saturated, psi	TSR, %
Granite	PG 64-22 Control	126.6	123.4	0.97*
Granite	PG 64-22 Zeolite	155.0	126.3	0.81*
Granite	PG 64-22 Control	89.8	68.2	0.76
Granite	PG 64-22 Zeolite	72.5	48.7	0.67
Granite	PG 58-28 Control	44.3	33.3	0.75
Granite	PG 58-28 Zeolite	36.2	19.2	0.53
Limestone	PG 64-22 Control	109.5	71.2	0.65
Limestone	PG 64-22 Zeolite	86.6	44.2	0.51
Limestone	PG 58-28 Control	26.0	28.8	1.11
Limestone	PG 58-28 Zeolite	39.1	38.0	0.97

Note: * Indicates Samples were individually mixed at 300 °F using oven dry aggregate

Figure 14 presents a sample containing Aspha-min® exhibiting a cohesive binder failure. It is believed that the binder was somewhat emulsified due to the moisture released from the Aspha-min®, causing the cohesive failure. It is possible that a cure time would dissipate the moisture in the binder, eliminating the potential of a cohesive binder failure. In Figure 15, the conditioned control sample exhibited an adhesive failure between the binder and the aggregate. But the unconditioned control samples also exhibited visual stripping resulting from adhesive failures between the binder and the aggregate. It is expected that the adhesive failure resulted from moisture remaining in the aggregate from the lower mixing and compaction temperature. However, the cohesive binder failure in the samples containing the Aspha-min® resulted in lower tensile strengths.

FIGURE 14 Example of Cohesive Stripping Failure – Granite Aggregate

FIGURE 15 Example of Adhesive Stripping Failure – Granite Aggregate

It is believed that the failing TSR values were possibly due to several factors, those being moisture retained in the aggregate, or due to residual moisture left behind by the microscopic foaming process of the zeolite. To evaluate these hypotheses, additional TSR tests were conducted with the granite aggregate as shown in Table 9. To determine if the lower TSR values were caused by moisture in the aggregate, TSR testing was conducted using oven dry aggregate. The aggregate was placed in a 250°F (121°C) oven prior to mixing to make sure there was no internal moisture present. Test results from the oven dry aggregate also resulted in failing TSR values; therefore the decrease in tensile strength is not believed to be solely due to internal aggregate moisture.

Next, the effect of any residual moisture from the zeolite was examined. This was accomplished by allowing compacted samples to sit undisturbed at ambient temperature for a period of one month before testing. This was done to see if any residual moisture would dissipate as the mixture was allowed to age. This "age" time is present in an alternate TSR test specification, AASHTO T 283, which states the compacted mixture must sit for a period of 72-96 hours at room temperature before testing. For research purposes, this time was increased to a full month to allow greater dissipation of residual moisture, if any was to occur. Test results after the one month shelf aging showed that this "age" time did not increase the TSR values to an acceptable value.

To determine if the moisture resistance could be increased, anti-stripping agents were then evaluated. First, one type of liquid anti-stripping agent was used, ARMAZ LOF 6500. This additive is routinely used with the granite aggregate source. For the control mixture, the liquid anti-strip visually reduced the adhesive failure, increased the unsaturated tensile strengths while the saturated tensile strengths remained the same as the control mixture without liquid anti-strip. For the mixture with zeolite, the liquid anti-strip increased the unsaturated tensile strengths, but it decreased the saturated tensile strengths, thus resulting in a low TSR value (0.38). The decrease in the saturated tensile strength may possibly be due to a reduction in binder viscosity from the liquid anti-stripping agent.

TABLE 9 Additional Tensile Strength Results for Granite Aggregate with PG 64-22 Binder

Anti-Stripping Additive	Mix Type	Indirect Tensile Strength		TSR
		Unsaturated, psi	Saturated, psi	
None	Zeolite w/ Oven Dry Agg. at 250°F	67.2	40.4	0.60
None	Zeolite w/ 1 month shelf age	131.5	57.2	0.43
0.75% LOF 6500	Control	104.7	90.5	0.86
0.75% LOF 6500	Zeolite	96.0	36.2	0.38
1% Lime	Zeolite	110.6	85.5	0.77
1.5% Lime	Zeolite; Two-stage addition	79.9	69.3	0.87
1.5% Lime	Zeolite; All Added Dry	90.2	67.3	0.75

Hydrated lime was then evaluated. Hydrated lime was used in two different percentages (1 and 1.5 percent), while for the 1.5 percent added hydrated lime, it was evaluated in two methods – all added dry and in a two stage addition (0.5 percent added to wet aggregate and the remaining percent added at the same time as the binder). For the addition of just the one percent hydrated lime, it was added to the dry aggregate at the same time as the binder. From the results in Table 9, the hydrated lime increased the TSR value to just below the minimum requirement for Superpave mixes.

As was mentioned before, the use of 1.5 percent hydrated lime was evaluated in two methods. First, 0.5 percent was added to the wet aggregate. This was performed to try and improve the adhesive failure exhibited in the previous trials. The remaining percent was added to the dry aggregate at the same time as the binder to possibly solve the cohesive failure seen in the previous trial as well. From the test results, this added amount of hydrated lime produced an acceptable TSR value. But the split addition process may possibly add unnecessary cost, so the 1.5 percent hydrated lime was evaluated again, but added all at once to the dry aggregate at the same time as the binder. Results indicated a decrease in TSR value to an unacceptable value.

Hamburg Wheel-Tracking Device

To validate the TSR results, test samples were prepared and tested in the Hamburg wheel-tracking device. This device is used to predict moisture damage of hot mix asphalt. It also has been found to be sensitive to several factors, including asphalt cement stiffness, length of short-term aging, compaction temperature, and anti-stripping treatments (*8*). All these factors have previously been observed as possible problem areas in the evaluation of warm asphalt mixes, so the test results from the Hamburg wheel-tracking device may be vital in accurately establishing a good performing warm asphalt mix.

Test results form the Hamburg wheel-tracking device are presented in Table 10. Also included are the corresponding TSR values for each of the mix types. From these test results, the Hamburg test results confirmed the conclusion that when no anti-stripping additives were included, the mixture containing zeolite had a lower resistance to moisture than the control mixture, as seen by the stripping inflection point. When describing the stripping inflection point, it is the number of passes at which the deformation of the sample is the result of moisture damage and not rutting alone. Illustration of the stripping inflection point is shown in Figure 16. It is related to the resistance of the mix to moisture damage. Stripping inflection points over 10,000 cycles, in a general sense, represent good mixes. Based on the Hamburg results, the split addition of 1.5 percent hydrated lime improved both the stripping inflection point and the rutting rate, when compared to the results with just zeolite added. In terms of rutting rate, this was an improvement of 63 percent. Rutting rate is defined as the slope of the secondary consolidation tangent, as seen in Figure 16. The addition of 1.5 percent dry lime resulted in no occurrence of a stripping inflection point 10,000 cycles and further improvement in the rutting rate.

TABLE 10 Hamburg Wheel-Tracking Device Results for Granite Aggregate

Mix Type	Binder	Treatment	Stripping Inflection Point, cycles	Rutting rate, mm/hr	Unsaturated Tensile Strength, psi	Saturated Tensile Strength, psi	TSR
Control	PG 58-28	None	2575	7.715	44.3	33.3	0.75
Zeolite	PG 58-28	None	1775	6.828	36.2	19.2	0.53
Control	PG 64-22	None	6500[1]	1.841	89.8	68.2	0.76
Zeolite	PG 64-22	None	3450	5.139	72.5	48.7	0.67
Zeolite	PG 64-22	1.5% Hydrated Lime 2 Stage Addition	8500[1]	1.912	79.9	69.3	0.87
Zeolite	PG 64-22	1.5% Hydrated Lime All Added Dry	NA	0.687	90.2	67.3	0.75

[1] Individual sample did not have a stripping inflection point; reported value is average of 10,000 cycles and recorded stripping inflection point of second sample seen in Figure 16. The addition of 1.5 percent dry lime resulted in no occurrence of a stripping inflection point 10,000 cycles and further improvement in the rutting rate.

The results from the Hamburg wheel-tracking device correlated well with the TSR values, validating the earlier claim that the addition of zeolite increased the potential for moisture damage. The split addition of lime resulted in a decrease in the rutting rate and an acceptable TSR value, so it may serve as a possible solution to the moisture sensitivity problem. The Hamburg results for the addition of 1.5 percent dry lime indicate a mixture resistant to moisture susceptibility while the TSR results were marginal. Generally, the Hamburg wheel-tracking test is considered to be the more rigorous evaluation of moisture damage as compared to the TSR test. Lime will also stiffen the binder (9), thus also providing a benefit in the rutting potential of warm mixtures that are compacted at a lower temperature (less than 250°F (121°C).

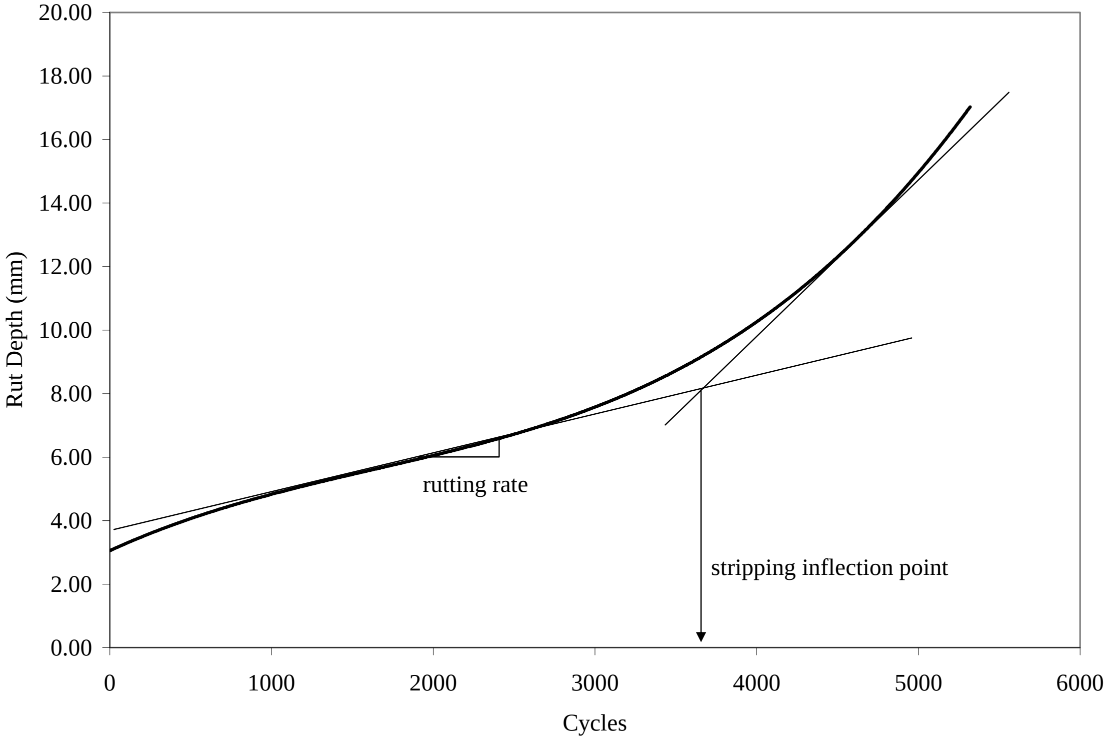

FIGURE 16 Hamburg Test Results, Defining Rutting Rate and Stripping Inflection Point

FIELD DEMONSTRATION PROJECT

In February 2004, a field demonstration project was constructed at Hubbard Construction's equipment yard in Orlando, Florida. The demonstration project was constructed on an existing parking lot 300 feet long by 60 feet wide. The existing surface was milled and tacked prior to paving. The paving consisted of two 12-foot lanes of a control mix and three 12-foot lanes of warm mix. Two NCAT engineers traveled to the site to monitor construction and collect samples.

The hot mix asphalt was produced at Orlando Paving Company's asphalt plant approximately two miles from the paving site. The control mix met the requirements of a Florida Department of Transportation Traffic Level C, fine-graded Superpave mix. The mixture was produced with crushed granite aggregate and 20 percent reclaimed asphalt pavement (RAP). Traffic level C is designed for 3 to 10 million ESALs with an N_{design} = 75 gyrations. The warm mix was produced by adding Aspha-min® zeolite to the control mixture at the rate of 0.3 percent by weight of total mix.

The Aspha-min® zeolite was introduced into the plant using a specially built feeder (Figure 16). A vane feeder controlled the addition rate and then the zeolite was pneumatically blown into the drum using an existing fiber addition line. The zeolite was introduced into the drum at the same point as the asphalt cement. Both the control and warm mix were produced at 130 to 140 tons per hour. Approximately 76 tons were used for the control section and approximately 112 tons of HMA were used for the warm mix section. The production and discharge temperature are summarized in Table 11. As can be seen from Table 8, the production and lay down temperatures for the Aspha-min® warm mix were approximately 35 °F less than the conventional mix. The moisture content of the virgin aggregate and RAP were reported to be 3.26 and 6.23 percent, respectively.

FIGURE 16 Feeder for Aspha-min® Zeolite

TABLE 11 Production and Lay Down Temperatures (*10*)

Mix	Temperature, °F			
	Discharge	Stack	Trucks at Plant	Lay Down Behind Screed
Control	336	155	307 to 320	293 to 315
Aspha-min®	300	150	265 to 275	256 to 260

Laboratory Tests

Samples were taken at the plant from both the control and Aspha-min® warm mix. Samples were compacted at Orlando Paving Company using both the SGC and the Marshall Method. The control mix was compacted at 310°F (154°C) and the warm mix was compacted at 270°F (132°C) (in the lab). Additional warm mix samples were compacted after a one hour oven aging period at the compaction temperature. The oven aging was done to assess the ability to silo the warm mix. Additional samples were compacted using the SGC for TSR testing. The compacted

TSR samples and loose mix to prepare APA samples were shipped to NCAT to complete the testing. The asphalt content and gradation of the control and warm mix are shown in Table 12. The warm mix was slightly finer than the control mix.

The average volumetric properties of both mixes are shown in Table 13. The average air voids of both mixes were essentially identical even though the compaction temperature of the warm mix was 40°F (22°C) lower. The gyratory air voids for the unaged warm mix was slightly higher than the control, but this also corresponds to a slightly higher VMA. The Marshall samples were compacted with 75 blows on each face. The Marshall Method air voids of the two unaged mixes were identical even though the Marshall Method has historically been very sensitive to compaction temperature. The Marshall Method air voids for the aged samples were higher. This could be due to aging of the binder or a dissipation of the moisture released by the zeolite. The 75 blows with the Marshall Method produced significantly less compaction than 75 gyrations with the SGC.

TABLE 12 Asphalt Content and Gradations for Aspha-min® Demonstration Project (*10*)

Sieve Size (mm)	Percent Passing	
	Control	Aspha-min® Warm Mix
19.0	100	100
12.5	93.5	96.5
9.5	88.2	91.7
4.75	61.7	65.8
2.36	40.9	43.1
1.18	27.5	28.8
0.600	20.1	21.1
0.300	14.0	14.9
0.150	8.0	8.9
0.075	4.9	5.9
AC %	5.33	5.40

TABLE 13 Demonstration Project Volumetric Properties (*10*)

Property	Control Mix	Aspha-min® Warm Mix	
	Unaged	Unaged	Aged
SGC Air Voids, %	4.96	5.24	5.04
SGC VMA, %	14.8	15.0	14.8
Marshall Air Voids, %	6.43	6.50	6.95
Marshall Stability (lbs)	2930	2853	2733
Marshall Flow	12.5	13.0	12.0

APA tests were conducted to compare rutting potential. The tests were conducted at 64 °C (147°F) with a 120 lb vertical force and 120 psi hose pressure. The average rut depth for the control mix was 4.22 mm with a standard deviation of 2.17 mm. The average rut depth for the Aspha-min® warm mix was 4.08 mm with a standard deviation of 0.19 mm. One of the control samples had a much higher rut depth than the remaining two samples (6.72 mm). There appears to be no effect of the Aspha-min® zeolite on rutting potential. This matches the findings of the laboratory study.

TSR tests were conducted on the samples compacted at Orlando Paving Company according to ASTM D 4867. Unlike the laboratory study, after saturation, the samples were conditioned with one freeze-thaw cycle before being introduced into the 140°F (60°C) water bath. The results are shown in Figure 17. Similar to the laboratory study, the addition of the zeolite resulted in a reduced TSR value as compared to the control.

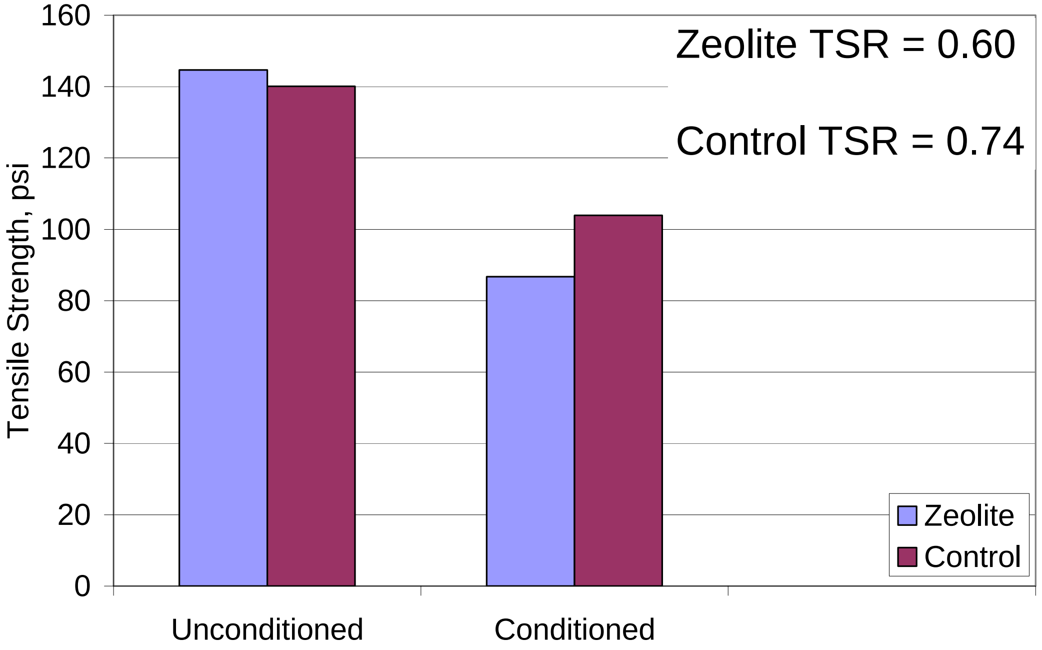

FIGURE 17 TSR Results from Hubbard Construction Demonstration Section

Field Placement and Compaction

The mix was dumped directly into the paver at the site. Breakdown rolling was conducted with two ten-ton rollers (Bomag BW9AS and Hypac C340C) rolling in echelon. The rolling pattern was established with the control mix and consisted of four static breakdown passes followed by two static finish roller passes. The finish rolling was completed when the surface temperature was between 160 and 180°F (71 and 82°C) for the control mix and at 150°F (66°C) for the Aspha-min® warm mix. The paving crew observed that the warm mix was more workable than the control mix. Densities were monitored by nuclear gage tests and cores. Three core samples were taken from each of the paving lanes. The results are shown in Table 14. Based on the core results, equal densities were obtained in the warm and control sections.

TABLE 14 Demonstration Project Density Results (*10*)

Lane	Density, pcf	Average Density, pcf
Control 1	139.1	140.2
Control 2	141.3	
Aspha-min® 1	141.2	140.1
Aspha-min® 2	139.0	
Aspha-min® 3	140.0	

An impromptu experiment was carried out to evaluate whether or not the mixes would tend to compact under traffic, if traffic was applied to the mixes while they were still warm. Once the control mix had cooled to a surface temperature of 110°F (43°C) and the warm mix had cooled to 120°F (49°C), a series of three nuclear gage readings were taken in a lane of each material. Then two static passes were applied to those areas and the nuclear gage readings repeated in the same locations. The density of the control section increased by 3.4 pcf (standard deviation = 0.4 pcf), while the density of the warm mix only increased by 0.3 pcf (standard deviation = 1.8 pcf). The maximum increase for the warm mix was 1.8 pcf. This would seem to indicate that traffic can be immediately placed on the warm mix when the surface temperature has cooled below 120°F (43°C) and possibly warmer.

Observations after One Year

In March 2005, the site of the Aspha-min® demonstration project was revisited to assess the condition of the pavement and to take cores to see if any indications of moisture damage were observed. The pavement had been used as an equipment parking area in the interim. No signs of distress were evident in either the Aspha-min® warm mix lanes or the control mix lanes. Five, six-inch diameter cores were taken from each section. The cores were wrapped in plastic wrap and placed in plastic bags to maintain their in situ moisture during expedited shipping back to NCAT. When the cores were received at NCAT, under water weights and saturated surface dry weights were determined, then the cores were conditioned to 77°F (25°C) in a water bath after which time the indirect tensile strength was determined. Each core was then placed in an oven to dry back to a constant mass before determining the dry weight to calculate density. The density and indirect tensile strengths are reported in Table 15. The maximum specific gravity values determined during construction were used to calculate air voids. The air voids in the warm mix were slightly higher than the control section. This may be due to normal variation. The indirect tensile strength of samples which are not allowed to dry out from their in-place moisture content can be used to assess any moisture damage that may be occurring in situ. The average tensile strength of the Aspha-min® cores is higher than the control. Even if the potential outlier is not included, the results are still practically the same. A few instances of adhesive failures were observed in the fine aggregate of both mixes. This indicates that in the field, the Aspha-min® warm mix was equally resistant to moisture damage as the control mix. It should be noted that these sections do not receive regular traffic. It is believed that traffic contributes to the occurrence of moisture damage.

TABLE 15 Core Densities and Indirect Tensile Strengths after One Year

Sample	Air Voids, %	Height, in	Tensile Strength, psi
Control Mix			
C1	6.6	1.9	195.2
C2	5.8	1.8	65.5[1]
C3	5.9	1.8	167.6
C4	8.9	1.7	152.2
C5	7.9	1.8	165.6
Average	7.0	1.8	149.2
Aspha-min® Warm Mix			
W1	8.8	1.8	160.1
W2	9.6	1.8	158.2
W3	8.0	1.8	172.1
W4	6.1	1.6	195.1
W5	7.6	2.1	141.2
Average	8.0	1.9	165.3

[1] Appear to be an outlier; average = 170.2 psi without this sample.

CONCLUSIONS

Based on the results from the lab testing using the Aspha-min® zeolite, the following conclusions were made:

- The addition of Aspha-min® zeolite lowers the measured air voids in the gyratory compactor. While this may indicate a reduction in the optimum asphalt content, at this time it is believed that additional research is required and that the optimum asphalt content of the mixture determined without the zeolite should be used. It should be noted that the optimum asphalt content of the mixture without the addition of the zeolite was used for all of the testing (with and without zeolite) completed in this study. Reducing the optimum asphalt content may negate the improved compaction resulting from the addition of the Aspha-min® zeolite.
- Aspha-min® zeolite improved the compactability of the mixtures in both the SGC and vibratory compactor. Statistics indicated an average reduction in air voids of 0.65 percent using the vibratory compactor. Improved compaction was noted at temperatures as low as 190°F (88°C).
- The addition of zeolite does not affect the resilient modulus of an asphalt mix. Improved density improves the measured resilient modulus.
- The addition of zeolite does not increase the rutting potential of an asphalt mix. The rutting potential increased with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder.
- There was no evidence of differing strength gain with time for the mixes containing zeolite as compared to the control mixes. The addition of Aspha-min® may not require a cure time for the asphalt mixture prior to opening to traffic.

- The lower compaction temperature used when producing warm asphalt with Aspha-min® may increase the potential for moisture damage. There appears to be two causes for this effect. First, lower mixing and compaction temperatures can result in incomplete drying of the aggregate. The resulting water trapped in the coated aggregate may cause moisture damage. Reduced tensile strength and visual stripping were observed in both the control and Aspha-min® zeolite mixes produced at 250°F (121°C).
- Various anti-stripping agents were evaluated to mitigate the potential for moisture damage. Hydrated lime appeared to be effective with the granite aggregate. The addition of 1.5 percent hydrated lime resulted in acceptable performance in terms of both cohesion and moisture resistance over the warm mixtures without hydrated lime.
- Hamburg results confirmed the test results produced by the TSR testing, as well as suggesting the lime will also assist in the rutting resistance of warm mixtures compacted at lower temperatures due to the lime stiffening the asphalt binder.
- Aspha-min zeolite was successfully added to a Superpave mixture containing 20 percent RAP during a demonstration project in Orlando, Florida. The addition reduced the production and compaction temperatures by approximately 35°F (19°C) while resulting in the same in-place density.
- Laboratory testing performed on field produced mix corresponds with the trends seen in the laboratory study.
- Field data indicated that, for a non-trafficked area, moisture susceptibility is not an issue after one year.

RECOMMENDATIONS

Based on the research conducted to date, the following is recommended when using Aspha-min® zeolite to reduce hot mix asphalt production temperatures:

- The optimum asphalt content should be determined without the addition of Aspha-min® zeolite included. Additional samples should then be produced so the field target density can be adjusted (e.g. If the air void content with zeolite included was decreased in the lab by 0.5 percent, then the field target density should be decreased by 0.5 percent).
- If the mixing temperature is greater than 275°F, then the same binder grade can be used in the design. If the mixing temperature is below 275°F, then either the high temperature grade can be bumped by one grade, or hydrated lime can be added to counteract the tendency for increased rutting susceptibility with decreasing production temperatures. Performance testing can be conducted to predict field performance.
- Tensile strength ratio testing should be conducted at the anticipated field production temperatures. If test results determined are not favorable, hydrated lime should be added to the mix as an anti-stripping agent to increase the tensile strength ratio.
- More research is needed to further evaluate field performance, the selection of the optimum asphalt content, and the selection of binder grades for lower production temperatures.

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